Response of soil erosion and sediment yield to the temporal variation of precipitation in the Loess Plateau

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Abstract

With climate change, precipitations in different regions have varied in different ways, which lead to the changes of hydrologic response, soil erosion and sediment dynamics characteristics. The variation trend of precipitation in the latest 50 years in the Loess Plateau, where the most intensive soil erosion in China happens, is that both the number of precipitation events and amount of precipitation decreased. However, the change of precipitation intensity is not clearly pointed out. In this paper, different scenarios of precipitation change were set to simulate responses of soil erosion and sediment yield in a typical watershed at the Loess Plateau by using a process-oriented soil erosion model. Simulation results were used to analyze the response characteristics of soil erosion and sediment yield to the variation of precipitation. It is disclosed that in the studied region, 1) soil erosion will not always be reduced significantly with the decrease of annual precipitation, because rainfall intensity is another key factor which will impact the soil erosion process; 2) the developed process-oriented soil erosion model can simulate the influence of rainfall pattern to soil erosion more accurately than that using averaged data or the RUSLE model; 3) under conditions of decreased precipitation and increased intensity of precipitation, surface runoff and potential soil erosion will decrease far less than precipitation, that leads to more arid soil and unstable ecosystem and environment in this region.

1. Introduction

It is well known that precipitations in different regions have changed in different ways under changing climate. Hulme (1995) and New et al. (2000) constructed a dataset of 100 year-precipitation distributions over the global in the twentieth century, which covers the largest temporal-spatial measured-precipitation data. Based on the trend of global warming, researchers (Allen and Ingram, 2002; Kharin et al., 2007) figured out that global mean precipitation would increase, accompanied with more extreme precipitation events and increased precipitation intensity. The importance of rainfall pattern such as peak intensity was also emphasized.

Precipitation and runoff are direct driving forces of soil erosion and sediment transport. Variation of precipitation will surely lead to the changes of surface runoff, soil erosion and sediment dynamics. Response of soil erosion and sediment transport to precipitation change has become an important issue under changing climate (West and Wali, 2002; Asselman et al., 2003; Yang et al., 2003), but such research using process-oriented method in complicated regions such as the Loess Plateau can rarely be seen in literatures.

The Loess plateau lies in the arid and semi-arid region in the Northwest China, which covers regions of the Middle and Northern Shanxi and the Western Inner Mongolia. As the center of loess deposits, it has the most intensive soil erosion in China. With the typical monsoon climate, the region has an annual precipitation of 150 to 700 mm. However, the potential evaporation can reach as high as 1400 to 2000 mm. Precipitation primarily occurs in summer and early fall seasons with high-peak and short-duration characteristics. The amount of soil erosion resulted from intensive surface runoffs generated during these storms contributed over 70% of annual sediment yield. At the Loess Plateau, a sub-watershed was identified as the coarse sediment source region covering 78,600 km^2, where total specific sediment yield is greater than 5000 tons/km^2·a and specific sediment yield for particle size larger than 0.05 mm is greater than 1300 tons/km^2·a.

On the other hand, human activities such as soil and water conservation measures, tillage measurements, and infrastructure construction, could change earth surface significantly so that soil erosion and sediment dynamics would be also changed correspondingly. Simple statistical analysis based on gauging data can not identify the effects of climate change and human activities to soil erosion and sediment dynamics separately. Thus, quantification of the response of soil erosion and sediment yield to the precipitation variation can only be achieved by numerical simulation of rain-runoff and soil erosion processes.

Based on previous studies, the objective of this study is to simulate responses of soil erosion and sediment yield at the coarse sediment source region in the Loess Plateau by using a process-oriented soil erosion model. Simulation results under different scenarios of precipitation change will be used to analyze the response characteristics of soil erosion and sediment yield to the variation of precipitation.

2. Precipitation Variation Scenarios

The trend of precipitation change in the last century at the Loess Plateau was commonly recognized that the precipitation amount was higher both in 1960s and 1970s, and then decreased till 1990s (Song and Zhang, 2003; Gao et al., 2005; Liu, 2007). According to the field data from those rainfall stations in the coarse sediment source region, the annual precipitation amount decreased about 10% (Figure 1). However, future precipitation change in the Loess Plateau has not been clearly projected in the scenario of doubled CO_2 and global warming. There is no consistent conclusion resulting from various global-scale simulations. For example, Yang et al. (2003) predicted that future precipitation in this region will decrease. Whereas both Allen and Ingram (2002) and Kharin et al. (2007) said that it would increase. Therefore, it is difficult to determine future precipitation scenarios for the coarse sediment source region due to the complexity and uncertainty of future precipitation variation.

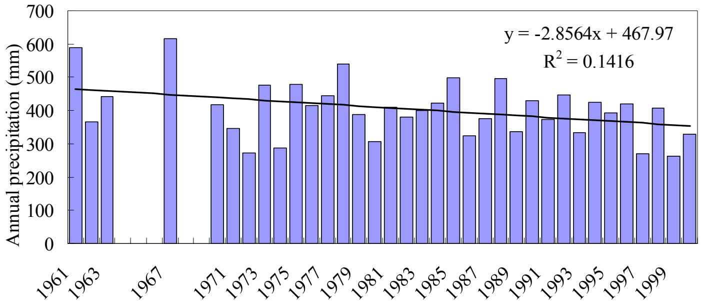

Figure 1 Variation of annual precipitation amount in the coarse sediment source region

Different conclusions have been made for the change of precipitation intensity in the Loess Plateau because of the lack of information on rainfall processes and inherent uncertainties of rain storms. Wang et al. (2003) figured out that the numbers of rain storms and the mean precipitation intensity decreased in the last 50 years. However, opposite conclusion was drawn by others. For example, An et al. (2006) analyzed rainfall patterns including the precipitation intensity and the duration in northwest China by using the detailed data of rainfall processes from 1970 to 2000. Following their analysis, precipitation amount in the coarse sediment source region decreased by 9.8%, intensity increased by 12.6%, duration in hours decreased by 16.5%, and duration in days decreased by 17.5% during 20 years.

In this study, several precipitation-change scenarios were set to tackle the responses of soil erosion and sediment yield to changed precipitation, and to investigate the influence of rainfall pattern to soil erosion and sediment yield based on the process-oriented soil erosion model.

A typical watershed, Chabagou in the coarse sediment source region was selected because there were several rainfall stations with detail-measured rainfall processes since 1960s. The data set in 1967 was selected as the baseline to represent the scenario of high precipitation amount in 1960s and 1970s. Three more scenarios were set to represent the decreased precipitation amount and different precipitation intensity in 1990s by scaling or modifying the data set of 1967 as follows:

(a) Reduce the rainfall amount in each time step by 10%, the scenario means that the precipitation intensity and precipitation amount will decrease together.

(b) Remove partial precipitation events in selected days to make the precipitation amount decreased while the precipitation intensity kept unchanged. With this modification, the precipitation amount of the scenario decreased by 9.1%, and the precipitation intensity kept 100.3% of the baseline.

(c) Remove partial precipitation events in selected days to make the precipitation amount decrease but precipitation intensity increase. With this modification, precipitation amount decreased by 10.3%, precipitation intensity increased by 13.3%, precipitation hours decreased by 20.8%, and precipitation days decreased by 15.2%. The characteristics of this scenario were similar to those in An et al. (2006).

All the scenarios above have the same rainfall events including their sequence, continuity, and the shapes of rainfall in each event, except for the removed rain days. This method can avoid any additional difference so that response of soil erosion and sediment dynamics to the precipitation change can be well investigated.

3. Simulation results analysis

Both the amount and the intensity of rainfall directly affect the processes of soil erosion and sediment dynamics. The impacts of these two factors have been taken into consideration with the rainfall and runoff factor R in the commonly used RUSLE model (Renard et al., 1997). By summing up the daily production of total storm energy E and maximum 30-min intensity I_{30}, the variation of factor R among the scenarios were obtained as shown in Table 1. Furthermore, a process-oriented soil erosion model (Li et al., 2007) was implemented together with rainfall-runoff and sediment transport models, which were integrated in the Digital Watershed Model (Wang et al., 2007), to simulate the processes of soil erosion and sediment yield with different precipitation change scenarios. The details of the model and the Chabagou watershed can be found in Wang et al. (2007) and Li et al. (2007). Simulated runoff depths and sediment yields from May to September are listed in Table 1 and presented in Figure 2. The results were used to analyze their response to the variation of precipitation.

Table 1 Factor R, simulated runoff and sediment results in different scenarios

Scenario	1967	1990s (a)	1990s (b)	1990s (c)
Precipitation (mm)	423	381	384	380
Variation of precipitation	—	-10.0%	-9.1%	-10.3%
Mean precipitation intensity (mm/h)	1.041	0.937	1.044	1.180
Variation of precipitation intensity	—	-10.0%	0.3%	13.3%
Variation of RUSLE R factor	—	-12.3%	-6.9%	-1.2%
Simulated runoff depth (mm)	31.2	23.2	23.2	30.6
Variation of runoff depth	—	-25.5%	-25.5%	-1.9%
Specific sediment yield (tons/km^2)	18780	13640	13620	18670
Variation of sediment yield	—	-27.3%	-27.5%	-0.6%

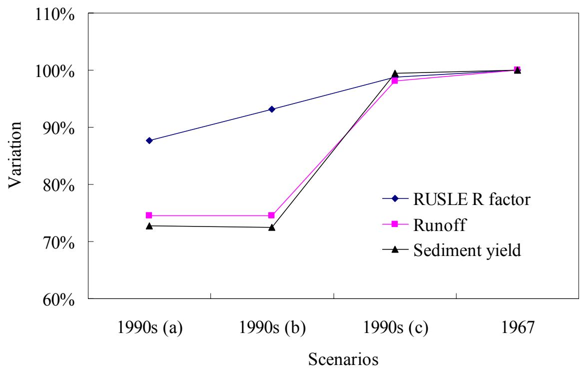

Figure 2 Comparison of the variations of factor R, simulated runoff and sediment yield in different scenarios

The RUSLE factor R varied monotonously and continuously with both the amount and the intensity of precipitation. That is, in the scenario (a) with decreased precipitation amount and intensity, the smallest R value was obtained; in the scenario (c), the increase of rainfall intensity mitigated the impact of rainfall amount decrease so that the value of factor R almost kept unchanged comparing to that of the baseline. Under the scenarios (a) and (b), the decrease of factor R was much smaller than that of the simulated sediment yield. This difference was caused by the method to calculate factor R. In the studied region, runoff generates only when rainfall intensity exceeds surface infiltration rate which depends on soil water content. When the rainfall intensity is smaller than the infiltration rate, runoff will not be generated and soil erosion will also not be generated correspondingly. Then, those-precipitation amount is not effective to runoff and sediment generation. However, all precipitations are considered to be effective for calculating the factor R. In the Loess Plateau, the portion of rainfall with intensity beyond the threshold covers only a small part of annual rainfall. The precipitation amount that the rainfall intensity is below the surface infiltration rate does not directly contribute to soil erosion. This is the reason why the decrease of sediment yield is greater that that of factor R. Therefore, factor R can not be well used to reflect the responses of runoff and soil erosion to the precipitation change.

The decrease of simulated runoff and sediment yield was much significant than that of precipitation amount in scenarios (a) and (b). Both rainfall intensity averagely reduction in scenario (a) and partial rainfall events removal in scenario (b) resulted in the reduction of the effective precipitation amount which will generate surface runoff and soil erosion significant smaller that that of the total precipitation amount. That is the right reason which leads to decrease of soil erosion and sediment yield significant smaller that that of precipitation amount. The increase of average rainfall-intensity with decreased precipitation amount in scenario (c) was achieved by removing some rainfall events with low intensity. These rainfall events have no contribution to runoff and soil erosion generation. Thus, there were no significant variations of runoff and soil erosion in scenario (c) although rainfall intensity and amount were changed.

It can be deduced from aforementioned analysis that both the amount and the intensity of precipitation are playing equal important roles in soil erosion and sediment yield, and should be considered together. In quantitative research, statistical mean values can not reflect the difference of rainfall events, and will lead to remarkable uncertainty when they are used for calculating runoff and sediment for arid regions. The infiltrated rainfall amount that yields little runoff will not be deducted from the total amount while calculating the rainfall and runoff factor R in the RUSLE model. Thus it can not effectively reflect the process responses. To accurately represent impacts of the temporal distribution of precipitation on soil erosion and sediment dynamics, process-oriented simulation would be more applicable.

As for the Middle Yellow River basin, under scenario (c) the decreased precipitation amount with nearly unchanged surface runoff means amount of water infiltration will significantly decreased correspondingly, which will leads to soil drying gradually. Thus, vegetation cover will become more difficult to be preserved, and the eco-environmental system in this region may be continuously deteriorated. Under this condition, water amount utilized by human beings will take a larger proportion of the total runoff so that soil and water conservation tasks will be more severe. More attentions should be paid to this case.

Due to the uncertainty of climate change in short time period, it has certain limitations to investigate the responses of soil erosion and sediment dynamics to the changed precipitation at the coarse sediment source region through only taking 1 year precipitation as the baseline for scenarios analysis. Firstly, the baseline with only one year may not have representative. Secondly, vegetation cover and underlying surface will change during long time period. Although the eco-environmental system has certain ability to self-adapt to the changed climate, it still needs artificial measures to facilitate it to adapt to those extreme climate conditions.

4. Conclusion

Soil erosion and sediment dynamics in the Loess Plateau is notorious and unique, and its response to the global climate change is more complex. A process-oriented soil erosion model was implemented in this paper to simulate sediment yield in a typical watershed under different precipitation-change scenarios. According to the simulation results and analysis, both the amount and the temporal process of precipitation are important to quantitative investigate the responses of soil erosion to the changed climate. Uncertainty will be introduced by only using statistical mean values used in the RUSLE model for the Loess Plateau.

The decrease of potential soil erosion is far less than that of precipitation amount under decreased amount and increased intensity of precipitation. The Loess Plateau will become more arid in this case, and thus the eco-environmental system will become more unstable. Further studies should be focused on the climate trend including the detail rainfall patterns in this region, responses of soil erosion to the changed climate, and effects of water-and-soil reservation activities on soil erosion and sediment dynamics.

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